Retrievals of Low Integrated Water Vapor Using MIR and SSM/T-2 Measurements

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***Abstract*—Satellite radiometric measurements at 150, 183.3±3, and 183.3±7 GHz have previously been used to retrieve integrated water vapor <1 g/cm over Antarctica. The effects of the frequency dependence of surface emissivity and the variation of surface temperature on the retrieval, which have not been closely examined in the studies, are analyzed. Using four days of near-concurrent airborne and satellite radiometric measurements, it is shown that the previously derived retrieval algorithm could overestimate or underestimate integrated water vapor by up to 0.1 g/cm^2, depending on whether the surface emissivity increases or decreases with frequency. The average of the absolute value of the bias for each flight case studied is $\leq$ 0.04 g/cm^2. Additionally, surface skin temperature is shown to vary substantially over a range from 240–270 K during these four days of measurements; the corresponding effect on the retrieval of integrated water vapor is comparable to that due to frequency dependence on surface emissivity. The quantitative correction needed for this effect is dependent upon the magnitude of integrated water vapor. At high values of integrated water vapor of 0.6–0.8 g/cm^2, the corrections are as large as 0.1 g/cm^2 for changes of surface temperature of ±10 K. A simple procedure is implemented to correct for this error, which significantly improves the retrieval. Correction for the frequency dependence of surface emissivity is nontrivial when using currently available satellite measurements; in order to properly correct this effect, an additional channel of measurements, e.g., at 220 GHz, is required.**

***Index Terms*—Millimeter-wave, radiometry, remote sensing, precipitable water.**

I. Introduction

WATER VAPOR is an important constituent for the radiative energy balance of the planet; in the polar regions it remains the most important greenhouse gas [1]. A reliable estimation of integrated water vapor (W) is essential for monitoring the state of W and its transport into and out of these regions; this information will potentially improve our understanding of the state of balance of ice sheets and their corresponding effect on global sea level [2]. The retrieval of W using satellite microwave radiometry has mostly been performed over the ocean surface and near the weak absorption line of 22 GHz [3], [4]. Radiometric measurements using the strong absorption line of 183.3 GHz are generally used for profiling of atmospheric water vapor [5]–[8]. However, for a dry atmosphere with W below about 0.8 g/cm^2, measurements near this strong line can provide an estimate of W both over ocean and land areas [9], [10]. The radiometric sensitivity to low W for this case is much higher than that at 22 GHz [9] and the high-precision retrievals of W have significant potential value for areas like Antarctica where the atmosphere is often dry throughout the year [1]. Recently, both Moore [1] and Miao *et al.* [11] performed a more systematic analysis of the problem and each independently derived a retrieval algorithm. They applied their algorithms to the measurements from the Special Sensor Microwave/Temperature-2 (SSM/T-2) over Antarctica and studied the temporal and spatial variations of the retrieved W. Additionally, surface emissivity at frequencies near 90 and 150 GHz are readily estimated after W is determined and surface temperature is independently measured [12]. The retrieved emissivity at these high frequencies could potentially aid in the studies of snow and sea ice properties, because snow and sea ice retrievals generally use only the transparent channels at frequencies ≤37 GHz [13]–[15].

The algorithm of Moore [1] uses only the 183.3±3- and 183.3±7-GHz channels of the SSM/T-2 as well as surface temperature from model reanalysis data, and thus avoids the impact of frequency dependent surface emissivity. However, the strong water vapor absorption at 183.3±3 GHz limits its applicability to extremely dry atmospheric conditions such as those found during winter in Antarctica. The algorithm of Miao *et al.* [11] primarily uses the measurements from the 150-, 183.3±3-, and 183.3±7-GHz channels of the SSM/T-2. The technique requires an assumption that surface emissivity is constant across the frequency range of 150–183 GHz, and the algorithm is developed at surface temperatures, T_s, equivalent to those at the lowest levels of an input ensemble of rawinsondes. Wang *et al.* [16] applied this algorithm to the Millimeter-wave Imaging Radiometer (MIR) measurements over northern Alaska as well as the Arctic region and retrieved W over both land and sea ice. MIR had an additional channel of measurements at 220 GHz [17]; thus, measurements from another frequency group of 183.3±3, 183.3±7, and 220 GHz are used to estimate W. It was found that concurrent W values estimated from the MIR data using both frequency groups differed by an amount that could not be explained completely by measurement or modeling errors. Wang *et al.* [16] reasoned that this discrepancy was predominantly due to the assumption of frequency-independent surface emissivity and, therefore, modified the algorithm to allow for a linear frequency dependence of surface emissivity across 150–220 GHz. The estimated W values from this modified algorithm are in very good agreement with near-concurrent rawinsonde observations from both the Alaska-Arctic and Midwest regions of the United States [18]. A shortcoming of this modified algorithm, which uses the measurements from four channels across the

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150–220-GHz frequency range, is its limited usefulness because none of the currently available surface-viewing orbiting microwave radiometers has measurements beyond 183 GHz. Thus, for practical applications, it is necessary to use the three-frequency measurements (e.g., SSM/T-2) to estimate W while recognizing that there is an uncertainty associated with the estimation.

In this paper, the effects of surface emissivity ε on the retrievals of W are quantitatively examined, using data acquired from the MIR measurements gathered during the Winter Cloud Experiment (WINCE) [19] and the Arctic Cloud Experiment (ACE) [20]. Additional radiometric data extracted from near-concurrent SSM/T-2 overpasses are utilized to estimate W, and the results are compared with those derived from the MIR measurements. The algorithm of Miao *et al.* [11] is essentially a regression approach based on calculations of brightness temperatures from a large ensemble of rawinsonde data. It pertains to a T_s equivalent to the average temperature at the lowest levels of rawinsondes used in the calculations and thus cannot effectively address the effect of actual T_s variation on the W retrieval algorithm. The effect is established as relatively small for a T_s variation of ±5 K from a simulation study [16]. This effect is reexamined in more detail below using the actual measurements from both MIR and the Moderate Resolution Imaging Spectrometer (MODIS) Airborne Simulator (MAS) [21] aboard the same ER-2 aircraft and the corresponding results are discussed.

TABLE I
TIMES OF SSM/T-2 OVERPASSES AND MIR FLIGHTS

Date	SSM/T-2	MIR	
	UTC	Start UTC	End UTC
Feb. 6, 1997	16:10	17:51	22:05
Feb. 9, 1997	15:34	16:19	20:02
Feb. 12, 1997	16:38	16:41	19:48
May 20, 1998	23:01	19:23	00:55

IV. CONCLUSION

Four days of near-concurrent MIR and SSM/T-2 measurements over both the Arctic region and Midwest region of the continental United States are analyzed to study the effects of surface emissivity $\varepsilon(\nu)$ and temperature T_s on the retrieval of column water vapor W. The thermal infrared T_s measurements from the OLS onboard the same satellite as the SSM/T-2 and from the MAS on board the same aircraft with the MIR aid in the analysis. It is proven that values of brightness temperature $T_b(\nu)$ measured almost simultaneously by the MIR and SSM/T-2 at the same frequencies (ν) compare very well; in particular, the absolute value of the bias for the comparison is ≤0.6 K for the 183.3-GHz channels. Consequently, excellent agreement is observed between the W values retrieved from the measurements of the two sensors. On average, the W values retrieved from the MIR are about 0.012 g/cm^2 higher than those retrieved from the SSM/T-2. This is primarily attributable to the slightly lower $T_b(150\text{ GHz})$ (about 2.7 K) observed by the MIR in comparison to the SSM/T-2.

Next, it is proven that the retrieval of W is affected to a lesser degree by the dependence of $\varepsilon(\nu)$ on ν, based on the analysis of the MIR measurements at 150, 183.3±3, 183.3±7, and 220 GHz. If the radiometric measurements are limited to the three frequencies of 150, 183.3±3, and 183.3±7 GHz, as with the SSM/T-2, then frequency-independent ε is assumed in the algorithm [10]. Such an algorithm is shown to overestimate W if $\varepsilon(150) < \varepsilon(220)$, and underestimate W if $\varepsilon(150) > \varepsilon(220)$. From the four days of MIR measurements over the Arctic and Midwest regions, the overestimation and underestimation of W are mostly $\leq$ 0.1 g/cm^2; the absolute value of the average bias estimated from each of these four days is $\leq$ 0.04 g/cm^2. Unfortunately, it is not trivial to correct for this error if the radiometric measurements are available only at the three channels between 150–183 GHz. Thus, it is important to consider this error source when applying such an algorithm to retrieve W from the SSM/T-2 measurements. A significant improvement in the accuracy of this retrieval is possible if the next-generation SSM/T-2 sensor includes an additional channel of measurements at 220 GHz.

Finally, the effect of T_s on the W retrieval cannot be ignored because of the potentially large T_s variations that occur in areas where the retrieval is valid. From the four days of OLS measurements over the Arctic and Midwest regions described above, T_s varies over a range of 240–270 K; therefore, the correction for the T_s effect of up to 0.1 g/cm^2 for the retrieved W values is proven necessary. To demonstrate the validity of these corrections, the previously reported [18] comparison between the MIR-retrieved W values with those derived from the near-concurrent rawinsonde observations is reexamined in this paper. It is demonstrated that, after applying the correction procedure for the T_s effect, the average difference between the MIR-retrieved and rawinsonde-derived W values is reduced from 0.072 to 0.035 g/cm^2. Therefore, if concurrent T_s measurements are available, the retrieval algorithm should include the procedure for correction of the T_s effect in an effort to improve the accuracy of the W retrievals.